# Ice Ages and Astronomical Causes:
## data, spectral analysis, and mechanisms

Richard A. Muller
Gordon J. MacDonald

link to Table of Tables and Figures

TABLE OF CONTENTS

PREFACE 5
1. BRIEF INTRODUCTIONS TO … 9
1.1 … the History of Climate 9
1.2 … Ice Age Theories 16
1.3 … Spectra 20
2. ASTRONOMY 25
2.1 Why Astronomical Forcing? 25
2.1.1 Resonant oscillator 27
2.1.2 Relaxation oscillator 30
2.1.3 Driven oscillator 32
2.2 Orbital parameters 33
2.2.1 Methods of calculation 34
2.2.2 Eccentricity 35
2.2.3 Precession 40
2.2.4 Obliquity 43
2.2.5 Insolation 45
2.2.6 Orbital inclination 48
3. SPECTRAL ANALYSIS 54
3.1 Introduction 54
3.2 The Fourier Transform 55
3.2.1 Basic properties 55
3.2.2 Glacial Fourier transform 58
3.2.3 The uncertainty principle 60
3.2.4 Periodogram 61
3.2.5 Sharp feature in the time domain 63
3.2.6 Fast Fourier Transform (FFT) 66
3.2.7 Padding with zeros 67
3.2.8 Aliasing 68
3.3 Blackman-Tukey method 70
3.3.1 example: eccentricity 72
3.3.2 example: Site V12-122 73
3.4 Tapers 77
3.5 Lomb/Scargle periodogram 80
3.6 Multitaper analysis 81
3.7 Maximum Likelihood Analysis 82
3.8 Maximum Entropy Method 87

3.9 Cross spectrum and coherency 89
3.10 Bispectra 91
3.11 Statistics of the Fourier Power Spectrum 93
3.12 Plotting power, log(power), and amplitude 97
3.13 Monte Carlo Simulation of backgrounds 100
3.13.1 Red and white noise 101
3.13.2 Prewhitening 103
3.14 Frequency estimation: the HWHM rule 104
3.15 Spectral width and shape determination 107
4. CLIMATE PROXIES 112
4.1 Oxygen isotopes 114
4.1.1 Physical mechanisms 114
4.1.2 Universality 116
4.2 The SPECMAP Stack and Marine Isotope Stage Numbers 120
4.3 Deuterium – a temperature proxy? 122
4.4 Integrative proxies and phase delay 124
4.5 Carbon-13 126
4.6 Vostok 128
4.7 Atmospheric $\delta^{18}O$ and the Dole Effect 133
4.8 $\delta^{18}O/CO_2$ Mystery 134
4.9 Other Sea floor records 135
4.9.1 terrigenous component 135
4.9.2 foram size: the coarse, or “sand” component 137
4.9.3 Lysocline: carbonate isopleths 138
4.10 Terrestrial records 139
4.10.1 Devils Hole 139
4.10.2 Loess 140
4.11 Features of the Data 142
4.11.1 The 100,000 year cycle 142
4.11.2 Sudden terminations and sawtooth shape 143
4.11.3 The 41,000 year cycle 146
4.11.4 Narrow Spectral Peaks 147
5. TIME SCALE AND TUNING 154
5.1 Effects of Chatter and Drift 154
5.2 Tuning 156
5.2.1 tuning example: Vostok 157
5.3 Band-pass filtering 160
5.4 SPECMAP: success and failure analyzed 163
5.4.1 Success 168
5.4.2 Failure of SPECMAP; triumph for tuning 169
5.4.3 SPECMAP and orbital inclination 174
5.5 Tuned and overtuned sedimentation rates 175
5.6 Overtuning 179
5.6.1 example 1: tuning a sine wave to eccentricity 179
5.6.2 example 2: tuning inclination to insolation 182

5.7 “Validation” of tuning -- invalid 184
5.8 Minimal Tuning 188
5.9 Overtuning: Examples from the Literature 189
5.9.1 Site 664 189
5.9.2 Site 659 190
5.9.3 Low Latitude Stack (Site 677 and MD900963) 191
5.9.4 Site 849 194
6. MECHANISMS, MODELS, AND THEORIES 196
6.1 Mechanisms 198
6.1.1 Radiative forcing and the Greenhouse effect 198
6.1.2 Atmospheric processes 199
6.1.3 Land-based mechanisms 202
6.1.4 Ocean-based mechanisms 204
6.1.5 Insolation forcing 205
6.2 Nonlinear Models 209
6.2.1 Nonlinear ice model 211
6.2.2 The AM Radio Nonlinear Model 213
6.3 Problems for models to address 215
6.4 Alternative astronomical models 216
6.4.1 Orbital inclination model 216
6.4.2 Statistical fluctuation 217
6.4.3 Resonant enhancement of the 95 kyr peak 218
6.4.4 Precession triggering 219
6.4.5 Multi-state climate model 221
6.4.6 Derivative of Eccentricity 223
6.4.7 Frequency modulation 224
6.4.8 Nonlinear memory model of Berger 225
7. ACCRETION CLIMATE MODELS 229
7.1 Origin and distribution of interplanetary dust 229
7.2 Transport to the Earth 231
7.3 Hitting the Earth’s atmosphere 233
7.4 Measurements of accretion rates 234
7.5 Scattering of sunlight model 236
7.6 Cloud cover model 236
7.7 Noctilucent cloud model 239
7.8 Ozone Model 241
8. EVIDENCE 244
8.1 The 100 kyr problem. 244
8.2 The Stage-11 Problem 246
8.3 The Causality Problem 250
8.4 The Unsplit Peak Problem 253
8.4.1 Simultaneous presence of eccentricity and inclination 257
8.4.2 Picking narrow peaks: circular reasoning? 259
8.5 The Absence of the 400 kyr Cycle 261
8.6 The bispectrum problem 263
8.7 The precession problem 264

8.8 The 41 to 100 kyr transition 268
8.9 Prediction verified: the 100 kyr accretion cycle 269
8.10 The 41 kyr problem 271
8.11 The sudden termination problem 272
8.12 The "unexplained" 70 kyr peak 273
8.13 Vostok 275
9. MILLENNIAL SCALE OSCILLATIONS 279
10. STATUS OF OUR UNDERSTANDING 285
APPENDIX 1. BISPECTRAL ANALYSIS 290
Computation of the Bispectrum 291
APPENDIX 2: MATLAB PROGRAMS 293
Note on vector and matrix programming 293
reading data 293
simulated data 294
adjusting to age tie points 295
interpolating to evenly-spaced time points 296
Fast Fourier transform 296
Taper 299
Background simulation 300
Random points with interpolation 300
Random points averaged 301
Random points convolved with Gaussian 302
Lomb/Scargle periodogram 302
Blackman-Tukey method 304
Maximum Entropy Method 305
Bispectrum 306
Band pass filter 307
APPENDIX 3: MAXIMUM ENTROPY PLOTS 309
APPENDIX 4: WEBSITES FOR DATA 311
REFERENCES 312

ACKNOWLEDGEMENTS

We are thankful to the many people who shared their insights with us, and who helped educate us on the many different areas encompassed by this book. We are particularly grateful to those who gave the manuscript a careful reading, and found many errors, especially Jonathan Levine, Daniel Karner, Ike Winograd, and Walter Alvarez. This work was supported in part by the U.S. Department of Energy Division of Environmental Sciences under contract number DE-AC03-7BSF00098. One of the authors (RAM) is particularly grateful to the Ann and Gordon Getty Foundation, for continuing to support his work as it wandered in an unpredictable path from *Nemesis* to the ice ages.